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THE USE OF NEAR-IR LIGHT TO MEASURE BODY FAT

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Preface

This need for body composition analysis is well documented in the literature. For example, the recent U.S. Surgeon General's Report on Nutrition and Health stated:

> "Obesity increases the risk for high blood pressure, and consequently for stroke; it also increases blood cholesterol levels associated with coronary heart disease."

The Surgeon General further adds that

> ". . . the health risks of obesity increase according to the degree and duration of obesity and the distribution of excess body fat."

This paper describes several different facts of body composition analysis. These include:

- Background on various methods that are currently in use for determining body composition. These methods include both indirect type of measurements (e.g. underwater weighing that uses the principle of buoyancy to derive percent body fat) as well as direct methods such as the near-infrared measurement techniques.
- A short background discussion on the methodology and techniques used for near-infrared measurement.
- Review of various technical papers that compare the near-infrared technique to other methods of assessing body composition. Included is a summary of the relative advantages and disadvantages of the use of near-infrared for body composition analysis.

1. INDIRECT METHODS

1.1. DENSITOMETRY [1]

The first practical method of determining body fat was developed near the start of World War II by Captain A. R. Behnke of the U.S. Navy. The Navy's interest was to define a method for selecting deep sea divers that would be at minimum risk for Caisson's disease (i.e. the "Bends"). Prior studies had shown that persons with higher body fat were more prone to Caisson's disease.

Behnke, using Archimedes principle, developed an underwater weighing method for determining body composition. In deriving this method, he made several fundamental assumptions:

- The human body can be considered made up of two parts. The first part is the total amount of fat in the body. The other part is the "Fat-free" part of the body. The weight of "body fat" was assumed to be 90% of the weight on an equivalent mass of water. The weight of the Fat-free portions of the body were assumed to be equal to 110% of the weight of an equivalent mass of water.
- That the percent of water in the body (i.e. level of hydration) of all people that are tested would be identical.
- That each person would have a constant relationship of the amount of bone muscle in the Fat-free body.

Underwater weighing

- Indirect method
  Assumes buoyancy is related to %BF
- Error Sources
  - Residual lung volume and body gases (Err=2.1%)
  - Bone Density (Err=2.1%)
  - Body Hydration (Err=2.7%)

  Accuracy = 3 to 4%
  Precision = 2 to 3%

  The "Gold Standard"

Am J Clin Nut 1987; Lukaski, H.C.

Figure 1. Brief Background

Many researchers have investigated the above assumptions. They have concluded that each of the assumptions introduce errors in the accuracy of body fat determination. Most researchers agree that the largest error is in the assumption that the hydration level of all individuals are identical at the time of the measurement. Obviously, the amount of water in the body is a function of when water is ingested and eliminated as well as the amount of physical activity that may have occurred, causing water loss.

It is also known that substantial error could be introduced by not being able to exhale all air out of the lungs during a lung volume test (the lungs act as a "flotation devices" and thus if one person is able to exhale or empty their lungs different than another person, errors in measurement are introduced).

It is generally accepted that underwater weighing has an accuracy of approximately three percent with a precision of between two and three percent.[1] (The word "accuracy" refers to the statistical relationship that two separate underwater facilities would calculate the percent body fat on the same group of individuals. The word "precision", sometimes referred to as "reproducibility" or as "reliability of measurement", is how close does the same underwater facility measure the same person when that person is re-tested).

Both "accuracy" and "precision" are stated as "standard deviations"; i.e. a statistical term which means that approximately 67% of the people tested would be within the "standard deviation" number shown. Conversely, "one standard deviation" also means that approximately one third of the people would have a measurement error that is larger than the number shown. Moreover, twice the size of the error shown (called "two standard deviations") would mean that 95% of the people tested would be within twice the error shown. Likewise, three standard deviations (three times the number shown) would contain approximately 999 people out of 1,000 tested.

To perform underwater weighing requires a sophisticated water tank where the water is kept at a constant temperature and is carefully filtered. The person is first weighed, then enters the water tank and is carefully re-weighed under water with his head fully submerged. In such weighing procedures, the effect of tank size, the experience of the volunteer to exhale all air out of his lungs while under water, play prominent roles to the success of the test.

Although it is obvious that underwater weighing techniques have severe limitations, most experts use it as the "gold standard"; i.e. underwater weighing is considered by most people as the official method of measuring body fat.

1.2. SKINFOLD CALIPERS

Underwater weighing requires specialized facility costing many thousands of dollars. Thus, very few people can take advantage of having their body fat determined using that technique.

For the above reason, a low-cost method was needed that would be able to provide body fat information to large groups of people. The most commonly used method involves measuring the sum of skinfolds at various sites of the body (similar to the old commercial of "pinch an inch").

There are two fundamental assumptions in developing skinfold caliper data:

- The assumption that the subcutaneous fat, i.e. the fat directly under the skin, is equal to 50% of the total fat of the body. (The other fat in the body is usually referred to as "intermuscular fat" - - - the type of "marbling" you see in steaks). This inherent 50/50 assumption appears to be valid in young adults. However, as people age, this assumption becomes less and less valid.
- The assumption is that the multiple body sites selected for the measurement of the skinfolds represent the average thickness of all the subcutaneous adipose.

To quote Lukaski[1]: "Neither of these assumptions have been proven to be true. Despite the contention that subcutaneous fat makes up about half of the total body fat, there is no data to support this statement. Furthermore, because there is little information on the distribution of fat in the body of the population at large, the validity of using skinfold equation to predict body composition is restricted to populations from whom these equations were derived."

Again quoting Lukaski, "The measurement of skinfold thickness is made by grasping the skin and adjacent subcutaneous tissue between the thumb and the forefinger, shaking it gently to exclude underlying muscle and pulling it away from the body just far enough to allow the jaws of the caliper to impinge on the skin."

Skinfolds

- Indirect Method
  Measures Subcutaneous Fat At Several Body Sites
- Error Sources
  - Subcutaneous is 50% of total body fat
  - Sites selected represent the average thickness of subcutaneous fat

  Accuracy = 3 to 9%
  Depending on population

  Precision = 5%
  For well trained operator

Am J Clin Nut 1987; Lukaski, H.C.

Figure 2. Brief Background

The above procedure depends on the judgement and skill of the person performing the measurement. Thus, in the technical literature there are papers that show quite good accuracy, even equivalent to the underwater weighing. However, other references, by just as qualified researchers, show very poor accuracy - - - as high as three times the error of underwater weighing.

Perhaps the biggest problem with skinfold calipers is the ability of most well-trained operators to be able to repeat the measurement on the same individual over a period of several days without having very large differences. This large precision error is why skinfold calipers are a poor method of providing meaningful information during diet programs or athletic conditioning.

1.3. BIOELECTRICAL IMPEDANCE

This is a relatively modern method for determining body fat. It is based on the fact that living organisms contain both intra- and extracellular fluids that behave as electrical conductors. Experiments show that low frequencies (approximately less than 1 kHz) will mainly pass through the extracellular fluid while at high frequencies (500 to 1000 times the lower frequency) the alternate current will penetrate both the intra and extracellular fluids. This approach has been shown that it can provide a highly accurate measurement of body water. Moreover, if the body is assumed to be in "balance", it allows an accurate calculation of the corresponding percent fat.[1]

The assumption that the body is in "balance" - - - that the fat content is exactly related to the water content of the body - - -requires adherence to a strict testing protocol including fasting for a considerable period of time before testing, voiding within thirty minutes of testing, as well as not allowing the body to change its electrolyte balance by the use of certain skin lotions, medications, etc. Moreover, to obtain the high accuracy using bioelectrical impedance, the recommended procedure is to have the person lie down on a comfortable surface while the small electrodes are attached to the fingers and the ankle areas of the body. Although this in general may not be unduly "invasive" it does require a certain amount of disrobing, particularly for females who have to remove stockings.

Bioelectrical Impedance

- Indirect Method
  Uses Electrical Current to Measure Body Water and Electrolytes
- Error Sources
  - Fasting for 2 to 8 hours and within 30 minutes of voiding
  - Perspiration, skin lotions, and metabolism changes

  Accuracy = 2.7%
  Precision = 2%

Am J Clin Nut 1987; Lukaski, H.C.

Figure 3. Brief Background

Provided that this protocol is met, bioelectrical impedance can provide accuracy similar to underwater weighing. However, unfortunately, most owners of bioelectrical impedance equipment either do not understand the need for these protocol items, or ignore the need. Thus, the procedure that is commonly used does not require fasting, etc., and may be prone to large errors.

1.4. OTHER METHODS

In Lukaski's review article,[1] he describes almost twenty other methods for performing bodyfat measurement. With the exception of body circumference measurements and near-infrared interactance, none of the other methods have found wide-spread use. In general, the reason they have not found widespread use is either the need for expensive equipment, or the need for invasive procedures (withdrawing blood samples, etc.).

For example, a radioactive tracer such as deuterium oxide can be orally ingested. After approximately one half hour, blood can be removed from the vein and laboratory analyzed. This method provides an excellent means of determining total body water. Unfortunately, however, it requires overnight fasting as well as this invasive technique. Thus, the

Others (not commonly used)

- TBW Via Radioactive Tracers (Deuterium Oxide)
- TBK Via Radioactive Potassium-40
- Bone Measurement at Multiple Sites
- Body Circumference At Multiple Sites
- Neutron Activation Analysis
- Computerized Tomography
- Ultrasound
- Near-IR Interactance (Lukaski's paper published before Futrex-5000 introduced)

Am J Clin Nut 1987; Lukaski, H.C.

Figure 4. Brief Background

accuracy of the measurement is somewhat dependent upon the truthfulness of the volunteer in really having provided an overnight fast.

Body circumference measurement techniques for predicting percent body fat have the advantage of being extremely low cost (only a good tape measure is required). Moreover, a number of researchers have provided conversion charts for using body circumferences to determine body fat. Unfortunately, like skinfold calipers, the accuracy of such an approach is directly dependent upon the population for which the equation was developed.

For example, the U.S. Navy uses body circumference measurements as its primary means of determining body fat among its military personnel. In general, the population they are testing are fit young men, and thus, the simplicity of simply using a tape measure coupled with the rather homogeneity of the subject group, provides it as a convenient method. Unfortunately, most studies show that the body circumference measurements can have errors as high as 9%, and therefore, it is not satisfactory in many applications.

Lukaski's paper also mentions near-infrared interactance. However, his paper was written approximately two years prior to the introduction of a portable instrument, and thus, the data shown for near-infrared interactance is not comparable to an instrument such as the FUTREX-5000.

2. BACKGROUND SUMMARY

Most experts consider the underwater weighing method of determining percent body fat as the official method. Unfortunately, the accuracy and precision of underwater weight is approximately 3% (one standard deviation). These relatively large errors are primarily due to:

- Residual air left in the lungs during measurement
- Differences in bone density between people
- Variation in body hydration between individuals

Since underwater weighing is generally accepted as the Official Method, all other methods must be compared to this Official Method - - - i.e. no other method of body fat measurement can be proven to have better accuracy than underwater weighing.

The following personal analogy may prove helpful in understanding this limitation.

UNDERWATER WEIGHING

Is The "Official Method"

Unfortunately it is an Indirect Method (Measures buoyancy not fat)

And its ACCURACY is limited (2+%)

YET all other methods must be evaluated against this "Official Method"

THUS, the ACCURACY of any other method can't be shown better than this Official Method

Figure 5.

I grew up in a relatively crime-ridden blue collar town. Because of the crime problem, the public schools attempted to provide strict discipline in the hopes of helping the education process. One part of the discipline process was the decision by the school administrators that the Master School Clock was the Official Method of measuring time in the school; each class room had a slave clock that read exactly like the Master School Clock. But unfortunately, the Master School Clock was almost thirty years old and did not run consistently. However, consistent or not, it was the Official Method of determining time in the school.

Each morning, when I arrived at school I reset my wrist watch to match the Master School Clock. On some days, I had to turn my watch forward five minutes, on other days I had to turn it back maybe fifteen minutes.

Even though I owned a very good watch - - - a watch that on Friday after school I would set it to the radio announced time, and it always gave the identical time as the radio until I left for school on Monday morning - - - it was always giving the <u>wrong time</u> when I got to school when compared to the <u>Master School Clock</u>.

One day I arrived at school five minutes early according to my watch, but unfortunately ten minutes late according to the Master School Clock. My teacher immediately suspended me from class and sent me to the principal's office for punishment. When I protested saying that I was not late, that my watch kept better time than the old, worn out Master School Clock, the teacher taught me one of the great lessons in life: "YOUR WATCH CANNOT BE BETTER THAN THE MASTER SCHOOL CLOCK BECAUSE THE MASTER SCHOOL CLOCK PROVIDES THE OFFICIAL METHOD OF DETERMINING TIME!" She further added that until someone formally notifies her of a new official method, all time keeping functions in the school will be performed using the Master School Clock.

The above analogy is somewhat similar to the Official Method of determining percent body fat. Although it is well known that underwater weighing is not highly accurate, it is based on a well-established scientific principle (i.e. Archimedes' Principle)and thus has been designated by many as the Official Method. Therefore, when any other technique for measuring body fat is being compared to the Official Method, it cannot be more accurate than the official technique.

Thus, for the measurement of body fat, it does not matter how accurate your procedure is, you cannot prove it to be more accurate than the official procedure you are comparing it to. At best you can prove it has the same accuracy as the official procedure, but never better than it. (This will be further explained).

3. DIRECT METHODS

All the previously described techniques for measuring body fat are "indirect methods". In "indirect methods", body fat is not being directly measured. What is measured is:

- Either Buoyancy which is then converted, through a series of assumptions, into percent body fat.
- Or Electrical Impedance which measures total body water which is then converted, using certain assumptions, into percent fat.
- Or Thickness of Skinfolds at various sites on the body which are then converted, using various assumptions, into percent body fat.
- Or Body Circumference Measurements, which are then converted, using certain assumptions, into percent body fat.

Obviously, it would be highly desirable to use a technique that provides direct measurement of body fat as opposed to measurement of some other parameter that needs to be mathematically converted to body fat.

DIRECT METHODS

SOLVENT EXTRACTION

1) Precisely weigh the subject

2) Grind up the subject

3) Thoroughly mix the puree

4) Take many subsamples and mix

5) Use solvent (e.g. ether) to remove all fat

6) Precisely weigh the fat

7) Calculate true percent fat

Accuracy = 0.1%
Precision = 0.1%

(Difficult to get volunteers)

Figure 6.

In the chemical laboratory, there is an excellent direct technique for determining percent fat. In that technique a "subject" (e.g. a piece of meat) is carefully ground and mixed into a puree. Small "subsamples" are taken from various parts of that puree and then combined and thoroughly mixed. That subsample would then have its fat removed by using a solvent such as ether. As anybody who has ever washed dishes knows, various types of solvents (for example, detergent) allow fat to be removed from a plate. Likewise, a solvent such as ether allows only fat to be removed from the muscle part of meat. By carefully using this technique you can "strip" all the fat from the meat, and then weigh the amount of fat and calculate the percent fat.

This solvent approach is commonly used for measuring the percent fat of ground beef in supermarkets as well as other types of meat measurements. If the procedure is carefully performed, the accuracy and precision are both within 0.1% - - - significantly better than can be obtained by underwater weighing.

Obviously, this destructive technique is not applicable to the measurement of people - - - even American law does not allow you to grind up people. The purpose for mentioning it is to illustrate that there are techniques that provide excellent accuracy in other applications of fat measurement.

4. A VARIATION OF THE DIRECT METHOD

The next section explains the near-infrared measurement principle. Briefly summarizing all organic materials (e.g. fat or protein) absorb light in unique portions of the spectrum. For example, we are all familiar with the childhood game of putting a flashlight in the palm of your hand in a darkened room and seeing the red glow. That red glow is related to the amount of oxygen that is saturated in the blood stream. By seeing the red glow, your eyes are actually performing a simplistic measurement of a chemical property of the blood (i.e. amount of oxygen) without having to cut open the hand.

Similarly, if you were able to see in the "near-infrared" portion of the spectrum - - - i.e. at wavelengths slightly larger than those wavelengths - - - the presence of fat when light is passed through the material will cause certain wavelengths to be absorbed by the material and certain wavelengths to be transmitted (just like the flashlight in the palm of your hand). Your hand glows red because the blue and green portions of the visible light from the flashlight is trapped, i.e. "absorbed", by the blood. Thus, at unique "near-infrared" wavelengths - - - approximately at 928nm - - - would provide a direct measure of how much fat exists.

This technique is now widely used in measuring samples of ground beef. By measuring the amount of this unique "near-infrared optical signature" in the original pureed meat, and then stripping the meat with a solvent and continuing to measure it until this unique glow disappears, a very exact measurement of percent fat can be determined. In fact, researchers have shown that using the near-infrared optical signature, measurement accuracy and precision of 0.01% is practical.

This approach, similar to the solvent extraction weighing approach, cannot be used on measurement of people. However, it can be used on animal studies, thereby, allowing a method for very accurately studying percent fat in animals.

5. NEAR-IR PRIMER

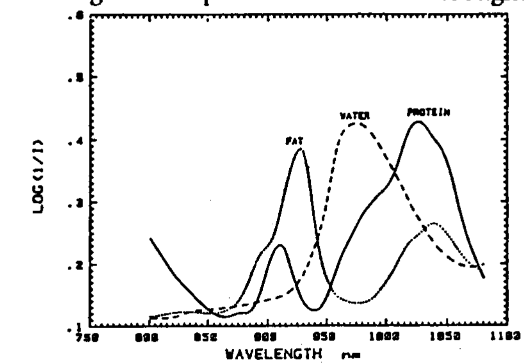
Approximately 1970, the U.S. Department of Agriculture expanded on the above destructive approach. They discovered a new and simple non-destructive method for providing measurements of organic constituents. That method also involved the use of near-IR light and is normally called "Near-IR Quantitative Analysis".[2]

As previously described, once you have wavelength outside of the visible part of the spectrum - - - wavelengths larger than 750nm - - - every organic constituent has a unique "glow". As shown on the attached graph, the "glow" of fat is uniquely different than the glow due to water and the glow due to protein.

NEAR-IR PRIMER

Discovered 20 Years Ago

- All organic compounds absorb Near-IR light



- The amount of energy absorption is linear with concentration

Percent = $C_0 + C_1$*(Function log 1/T)

Using this approach, over 100,000 NIR instruments are currently in use.

For example:

- Protein, Oil, and Moisture in grains
- Maturity in fruits
- Fat, Sugar, and Moisture in candy
- Protein, Oil, Moisture, and Starch in foods

Figure 7.

What the U.S.D.A. discovered was that if you shined the light through any type of item - - - e.g. an apple, grain, candy, etc. - - - you could measure each of the organic constituents by careful measurement of these glows and then converting these optical measurements, by use of a sophisticated mathematics into percent concentration. Fortunately, this U.S.D.A. discovery occurred approximately the same time as microprocessors were invented. Thus, the somewhat difficult mathematics became rather easy to be accomplished.[3]

Using this approach, well over 100,000 near-infrared instruments are currently in use around the world. These instruments provide a multitude of different types of measurement. For example:

- Grains - Rapid tests are made on almost every truck load of wheat and barley throughout the world in order to sort them depending upon their protein and moisture content. Similarly, soybeans are also being sorted the same way based upon not only protein and moisture, but also the oil content.
- Fruits - Apples, pears, grapes, and many other fruits are now being sorted based upon their taste qualities, maturity, and presence of internal diseases.
- Candy - Most major candy manufactures use near-infrared instruments to control the amount of moisture (which affects how long candy can survive on a store shelf) and their fat content (which greatly affect the profitability of the candy company). Typical measurements include fat, sugar, moisture content.
- Foods - Almost any type of food that is sold in the supermarket has been tested by near-infrared. Such tests include measurements of baked products such as breads and cookies, for moisture and protein content, measurement of food safety (e.g. whether or not there are foreign objects mixed in with the

food), and a multitude of other types of measurements required to produce high quality food.

6. NIR MEAT ANALYSIS

In the U.S.A., approximately 25% of all meat that is sold is ground beef. Moreover, according to American law, ground beef (sometimes called "hamburger") cannot be adulterated - - - ground beef cannot have any added spices, grains, or any other material accept natural beef.

Because the average supermarket chain in the United States operates on extremely small profit margins (typically profit of 0.5 percent or less) it is critical that their meat department be as profitable as possible. Approximately 30% of the total money spent in supermarkets is for meat products, and thus, the ground beef profitability is really the keystone of a profitable supermarket.

In the United States, there are several different laws governing the allowable percent fat for ground beef. The federal law requires that no ground beef be sold with fat content over 30%. Each state has different laws. However, in most states the law is that if the supermarket guarantees lower percent fat (for example, extra lean at 15% fat) then if the supermarket delivers ground beef with higher fat then it has violated the law. Such violations are a marketing disaster for the supermarket because the newspaper treats it as if the consumer is being swindled.

For that reason the supermarkets tend to try to be sure they are below the legally defined percent fat. However, by being too much below they lose valuable profit. This is obvious when you consider that lean meat (meat with no fat) has a value of about $3 per pound and pure fat trimmings only have a value of about $0.05 per pound. Thus, obviously the more fat trimmings you can include in the ground beef, without violating the law, the most profit you can earn.

Since 1974, near-infrared instruments have been widely used in the U.S. supermarkets in order to allow the local butcher to satisfy the law and yet provide as high a fat product as legally allowed. In such applications, comparisons of the near-infrared measurement can be made against the ether extract method that was previously described. Typically on pureed meats the near-infrared approach shows an accuracy of 0.1%. Saying this differently, the near-infrared technique has proven itself that compared to an official laboratory approach, it can provide accuracy of 0.1%

On ground beef, unlike pureed samples, you can actually see the white fat portions mixed in the meat. This introduces "sampling errors" into the measurement, and thus, the accuracy of the near-infrared becomes equal to the sampling error which is about 1%.

On a different type of product such as sausage, which you can have grain, meal, spices, and other additives added, near-infrared is commonly used to measure percent fat and has proven to have an accuracy of 0.2% compared to the ether extract method.

7. USING NEAR-IR ENERGY TO MEASURE BODY FAT

Traditionally, two different near-infrared quantitative measurement techniques have been used in industry and agriculture[4]:

- Analyzing the light that is reflected off the surface of an object - This approach is quite useful in measuring surface characteristics (for example, oil on the skin) but provides little, if any information concerning the chemistry that's under the skin.
- Analyzing the light that is transmitted through an object - When light is shined on an organic object (e.g. a hand), a small amount of the light is transmitted through the object. By analyzing the change in the spectrum as it passed through the object, the chemistry of the object's interior can be accurately determined. In this "transmittance approach", surface characteristics such as color have no affect at the wavelengths of interest. However, using transmittance does require access to both sides of the object; the side where the light goes in, and the side where the light comes out.

In the early 1980's the U.S. Department of Agriculture's ("USDA") began studies on whether or not near-infrared techniques can be used to measure body fat in humans. This research used a new type of measurement technique - - - Near-IR Interactance.

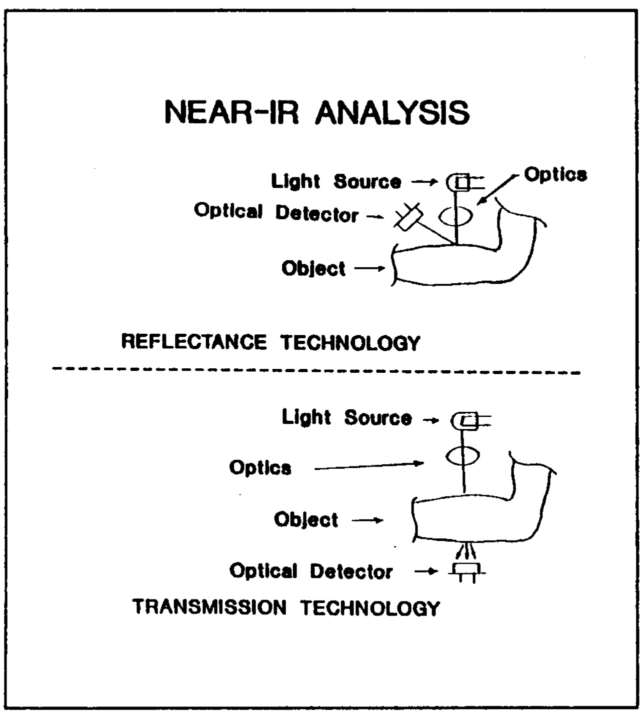


Figure 8.

The new NIR Interactance Technique is a compromise of the features of both reflectance and transmittance. Using the interactance approach requires that the optical detector (i.e. the "Light Out" shown in Figure 9) must only "see" light that emits from the inside of the body, not light that reflects off the surface of the skin. This is accomplished using opaque "spacers" that contact the skin and surround the detector, that prevent surface reflected light from "hitting" the detector.

Light enters the body (see the "horseshoe" shown in Figure 9) and as the light collides with the various internal components of the body (water, fat, blood vessels, bone) the light is scattered in all directions.

Some of this scattered light re-emits from the body at the site where the detector is located.

The change in spectra from the light that originally entered the body, compared to the spectra that comes out of the body is due to the internal chemistry of the body. Thus, the interactance approach has the ease of a reflectance measurement (requires access to only one side of the body), and yet the measurement is of the chemistry inside the body.

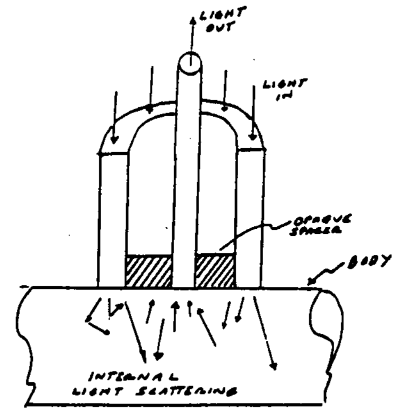
The USDA combined an interactance "measurement probe" with a highly sensitive, computer-operated optical instrument --- a scanning spectrophotometer. Such an instrument provides optical information over a large number of wavelengths, thus allowing studies of which wavelengths, or combination of wavelengths, could provide the most accurate measurements.

For the study of measuring percent body fat, the initial USDA study performed interactance measurements at the five sites typically used for skinfold measurement on a total of 53 men and women.[5] Figure 10 illustrates the type of spectrum data that was derived. The bottom two graphs show the spectrum if measurements had been made on pure water and on pure fat.

The top two curves represent two different individuals, one individual that had a high amount of fat at the triceps and

NIR BODY FAT ANALYSIS

Original Research on "NIR Interactance"



	N	Age	Wt	Ht
Males	20	41(11)	79(11)	176(7)
Females	33	43(14)	61(14)	164(7)

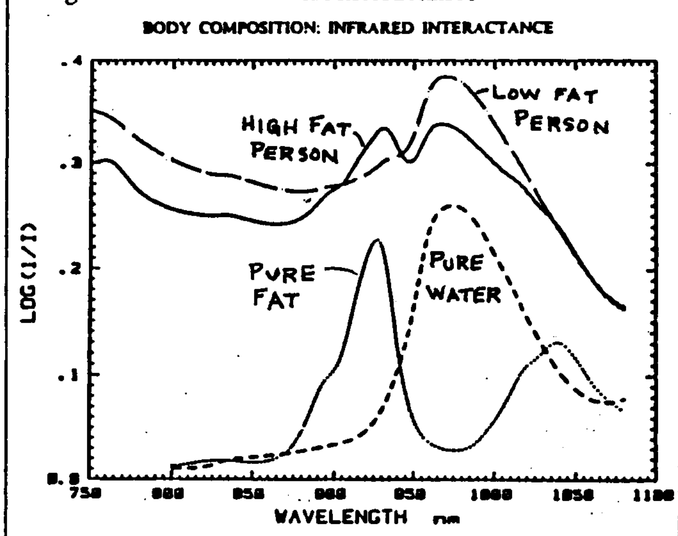
Measurements at 5 body sites

Am J Clin Nut 40:1984; Conway et al

Figure 9.

NIR BODY FAT ANALYSIS

Original Research on "NIR Interactance"



Am J Clin Nut 40:1984; Conway et al

Figure 10.

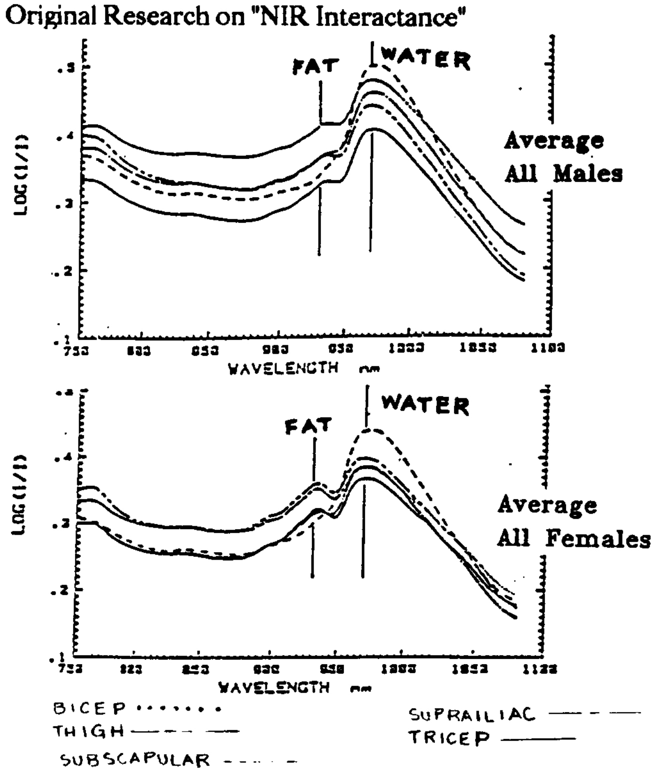
another individual that had a low amount of fat at the triceps. You will notice that there is a distinct change in the shape of the curves around 945nm. This occurs because for a lean person (i.e. a person with low percent body fat), more than 70% of body weight is water. Thus, it isn't surprising on the lean person, the maximum height of the curve occurs about the same place where pure water would peak (approximately 970nm). Moreover, for a lean person you would see very little "bump" (normally called near-infrared "absorption") occurring at the peak of the fat band approximately 928nm.

This condition is drastically different for the high fat person. You will note that for the high fat person, that person's curve shows an absorption (i.e. bump) near 928nm; i.e., has an absorption in the fat band. Since a high fat person must have less water in the body, (i.e. the fat plus water plus the protein in the body adds up to about 100%), it isn't surprising that the person's water "bump" at 970nm has diminished.

Another way of viewing these two curves is to note what happens as percent fat increases. As fat increases, the portion of the curve between 940nm and 950nm twists in a clockwise direction - - - the higher the fat, the more this rotation.

In fact, subsequent studies showed that the amount of this twist (rotation) is directly proportional to the amount of fat at that body location.

Original Research on "NIR Interactance"



Am J Clin Nut 40:1984; Conway et al

Figure 11.

The top part of Figure 11 shows the average data for all males that were in the study. Individual curves are provided for each of the five body sites that were measured. The bottom figure provides similar data for the females. By comparing the male versus the female spectrum curves confirms the well-known fact that, on the average, females have higher fat values than males.

Figure 12 illustrates the Near-IR accuracy obtained from Conway et al when all five measurement sites are used. The data show that if deuterium oxide was used as the official method (prior work had shown that that was equivalent to underwater weighing) near-infrared interactance correlated extremely well to it. In fact, near-IR correlates as well as one official underwater weighing laboratory correlates to another official underwater weighing laboratory.

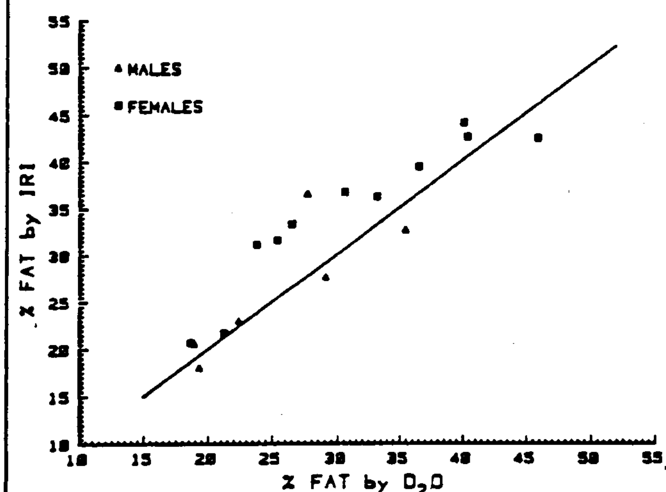
The data also showed that near-infrared did reasonably correlate to skinfold ("SF") and to the ultrasonic method ("US"). However, such correlations were much poorer than to the official method. This is as would be expected because the official method also correlates much poorer to SF and US. (Remember that skinfold analysis uses the implicit assumption that the subcutaneous fat is exactly one half of the total fat in the body. Such assumption is valid for college age individuals. However, the study by Conway et al covered individuals up to the age of 65. In fact, as shown in Figure 9 the average age for males and females was approximately 42 years old).

This pioneering research by Conway et al was followed up by a second paper by the same authors. That paper appeared in a book entitled "Invivo Body Composition Studies".[6]

Original Research on "NIR Interactance"

• Research Results

	NIR	
	R	SEE
D_2O	0.94	3.0
SF	0.55	4.4
US	0.84	4.7



Am J Clin Nut 40:1984; Conway et al

Figure 12.

The second study involved fifty-three men and women ranging in age from twenty-three to sixty-five. Their percent body fat varied from a low of 12% to a high of 50%. On this population they compared the near-infrared approach to skinfold calipers, deuterium oxide (D_2O), and underwater weighing. The near-IR test instrument was a full scanning, computerized spectrophotometer.

As shown in Figure 13, the near-infrared results provided the highest correlation to deuterium oxide. This was as the USDA expected because deuterium oxide is a highly reliable analytical tool.

Also as expected, the worst correlation was between near-infrared and skinfold calipers. It is well known that the accuracy of the skinfold caliper approach is very dependent upon the type of population being measured - - - and since the population in this particular study covered a wide range of age and body fat, caliper results were expected to be poor.

NIR BODY FAT ANALYSIS

Single Site Versus Multiple Sites

- 53 men and women
- Ages 23 to 65
- Percent body fat 12 to 50%
- NIR vs SF, D_2O, and UWW

Data from Computerized Spectrophotometer

	D_2O	UWW	SF
NIR avg 5 sites	0.90/3.2	0.85/4.3	0.982/3.9
NIR avg Tr & Bi	0.90/3.2	0.87/4.2	0.82/3.9
NIR Tr only	0.88/3.5	0.84/4.5	0.84/3.7
NIR Bi only	0.90/3.2	0.89/3.8	0.81/4.0

Simulated 2 Wavelength Instrument

	D_2O
NIR Bi only	0.72/6.4
NIR Bi + Ht	0.82/5.2
NIR Bi + Ht + Sex	0.88/4.0
NIR Bi + Ht + Sex + Wt	0.90/3.1

Bk "In Vivo Body Composition Studies" '86

Figure 13.

Perhaps the most interesting result was the startling conclusion that near-infrared provided the identical accuracy to D_2O whether the near-IR instrument measured five sites on the body (correlation = 0.90 and accuracy = 3.2%) or whether the near-IR instrument measures only at the biceps site (correlation = 0.90; accuracy = 3.1%).

Even more surprising was that the biceps site provided the highest correlation to underwater weighing (R = 0.89 and accuracy equal 3.8%). These unexpected results have subsequently been confirmed by other researchers:

- Single site (biceps) near-IR measurements, using the mathematics in the Conway et al paper,
- Do provide identical accuracy as if multiple sites were used, and
- Is equal to the accuracy of the underwater weighing procedure.

These near-IR results were based upon purely optical information; no physical data (e.g. height, weight) were used in the equations. However, the optical data that was used was based upon a sophisticated mathematical algorithm. The derivation of that algorithm is beyond the scope of this paper; however, it involves "a ratio of two independent second derivative terms derived from the basic optical spectra information".

The consequences of using "normalized second derivative math" is that a minimum of six separate optical measurements are needed to provide the body fat measurement. These six optical measurements are combined in a single optical term so that a simple linear regression could be performed:

- Percent Fat = $C_0 + C_1 \times [d^2(\text{Log } 1/T)_A / d^2(\text{Log } 1/T)_B]$

where:

- C_0 and C_1 are calibration constants
- $d^2(\text{Log } 1/T)$ is the second derivative of the optical spectra curve at wavelengths "A" and"B".

In attempting to rationalize why the single site measurement provided the best results using this complex algorithm, the following two rationales were presented:

- The percent fat at the biceps has a direct relationship to the total percent fat of the human body.
- The accuracy of the official methods of determining percent fat (e.g. underwater weighing or D_2O) is relatively poor, thereby limiting the potential improvement in accuracy by using near-IR at multiple sites on the body.

Although the Conway et al paper did not address either of these two possibilities, it did conclude that the near-IR biceps measurement, using sophisticated mathematics, provides the identical accuracy as the official methods.

Furthermore, Conway et al postulated that a low-cost instrument could not be manufactured using the sophisticated, six wavelength math that they had used. (It is usually assumed that the cost of an instrument is linearly related to the number of optical measurements required to be made.)

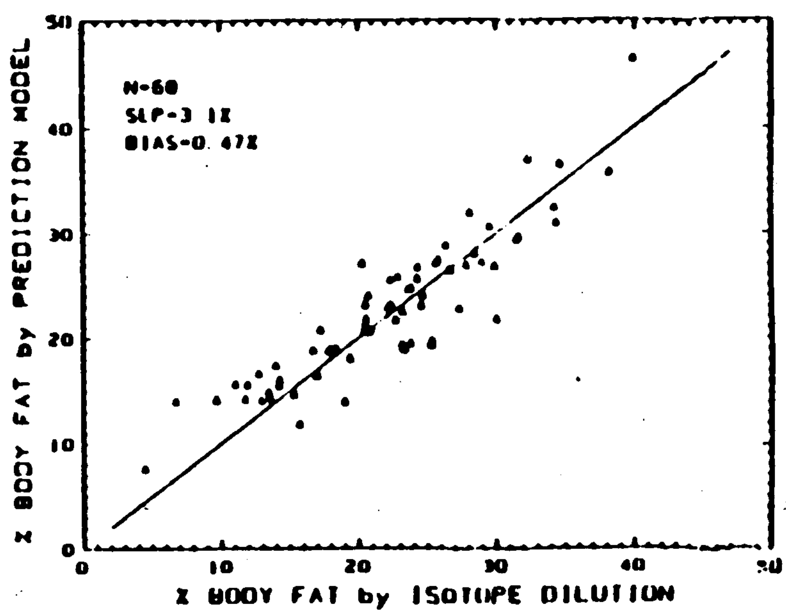


Fig 25.5 Relationship in 68 subjects (Study 2) between percent body fat as predicted by the IRI 50 nm smoothed model and percent body fat as estimated by the D_2O dilution technique. The IRI prediction equation was based on data (IRI and D_2O) obtained in 52 subjects (Study 1). The line shown is the line of identity.

Bk "In vivo Body Composition Studies" '86

Figure 14.

For the above reason, they investigated the possibility of using only two optical wavelengths. They showed that if they only measured at two optical wavelengths, the correlation at the biceps to D_2O was limited to 0.72 with an accuracy of 6.4% - - - essentially the same type of accuracy that is obtained from skinfold calipers.

However, if certain physical data was also included in the multiple linear regression equation - - - i.e. the two optical wavelengths at the biceps, plus the height, weight and sex of the individual, they obtained identical correlation and accuracy as the six wavelength instrument previously described. Saying this differently, they showed that using only two wavelengths plus physical data on individuals, they were able to get the identical accuracy as when using six wavelengths with no physical data.

Figure 14 illustrates the excellent results obtained using the two wavelengths plus physical data. This research provided the basis for the development of the FUTREX-5000 instrument.

8. WHY SINGLE SITE?

In an attempt to understand why the single body site (i.e. the biceps) provides identical accuracy as multiple sites, a test on hogs was performed. This test involved approximately 400 hogs each of which were measured at 11 different body sites.[7]

After the normalized second derivative near-IR measurements were made, the hogs were sacrificed and then ground using a typical supermarket meat grinder. The ground meat was then well mixed (i.e. blended) and then fine ground until it became a pureed sample. The entire pureed sample was then statistically sub-sampled. The sub-samples were combined, then well mixed. The resultant sample was considered representative of the entire hog.

The fat in this sample was analyzed using the solvent (ether) extract method. This official chemical method was proved to have an accuracy on these types of samples of 0.2%.

Why Single Site?

SWINE STUDY

- 400 Hogs
- Each hog measured at 11 sites
- Hog then slaughtered, ground, well mixed, pureed. Then statistically sampled.
- Total fat analyzed via solvent (ether) extraction. (Solvent method proved accuracy = 0.2%)

RESULTS

No. Sites	11	7	5	3	1
Accuracy	0.2	0.2	0.5	1.0	2.8%

UWW 5 PIGS

Accuracy of UWW = 2.9%

Trebor Research Program

Figure 15.

This method of measurement of meat is similar to the method used in over 3,000 supermarkets in the United States. In those supermarkets, near-infrared instruments are used to measure ground beef with a demonstrated accuracy of 0.2% when compared to the ether extract test.

The results of the hog study are provided in Figure 15. As shown, when all 11 sites were used for the measurement, the accuracy was 0.2%. This is not surprising because of the vast supermarket experience.

It was further shown that if the best seven sites were used, the accuracy remained 0.2%. However, if the number of sites was reduced to five, the accuracy diminished to 0.5%.

Likewise, for the best three sites, the accuracy became 1% and the best single site the accuracy was 2.8%.

It is believed that this is a significant finding - - - i.e. that the measurement of hogs at a single body site provided essentially the identical accuracy as single site measurement provides on people.

To partially substantiate these results, a small study was then made whereby five hogs were measured using underwater weighing techniques.[8] The test procedure used a special sling that allows weighing the animals out of water and weighing them under water. An oxygen mask was provided allowing the hogs to breathe while they were under water. To do this test, the pigs were tranquilized and an artificial method was used that caused the pigs to exhale most of the air in their lungs during underwater weighing. At the completion of the hydrostatic tests, the hogs were sacrificed and their body fat determined via the ether extract method.

Although it is recognized that this limited underwater weighing test was not optimum, it did provide the interesting result that the underwater accuracy was 2.9%. This is essentially identical to the 2.8% accuracy obtained by near-infrared on a single site on people.

It is believed that these tests on hogs provide credence that the reason that a single site on humans provides the same accuracy as multiple sites is due to the inherent errors in the official method of performing body fat measurement; i.e. the inherent errors in underwater weighing techniques. Saying this differently, if it was permissible to calibrate a near-infrared instrument by grinding the subjects up and performing an ether extract test, then multiple sites probably would provide better accuracy than the single site. However, since the accuracy of the official underwater weighing method is limited to approximately three percent, no additional accuracy can be obtained using near-IR measurements at multiple sites.

9. FUTREX-5000 INTERACTANCE INSTRUMENT

In 1988, a commercial instrument was introduced that uses the interactance measurement technique that had been pioneered by the USDA. This instrument, the FUTREX-5000 Body Composition Analyzer (Figure 16) performs optical measurements at two wavelengths plus has the ability of entering certain physical characteristics of the person being measured. The optical measurements are made at approximately 940 nanometers and 950 nanometers - - - those two wavelengths that were shown by the USDA to provide the measurements. The physical parameters used were height, weight, sex, and the amount of physical activity the person engaged in.

The FUTREX-5000 is designed to measure percent of body fat in either of two different ways:

- Either using a single body site (recommended at the biceps of the prominent arm). At this site the two wavelengths are measured and the physical parameters are used to provide the body fat measurement.
- Or using it at the same five measurement sites that skinfold calipers are used. In this approach, no physical parameters were used to perform the body fat measurement.

Figure 16. FUTREX-5000

In the three years since the commercial product has been introduced, approximately 10,000 instruments have been installed in medical offices, health clubs, diet clubs, athletic teams, and schools. A recent survey of these instrument users indicate that essentially no one is using it at the multiple sites - - - everybody is using it at the single site of measurement at the biceps of the prominent arm.

In accordance with this recent survey, the most desirable features of the unit are:

- The ability to perform a measurement in only a few seconds.
- The subject does not need to disrobe.
- Measurement can be made in any body "state" (i.e. no fasting required, measurement can be made before or after exercise, etc.).
- The ability of the instrument to provide a printout, not only of the body composition but also of a full Fitness Analysis.

10. INDEPENDENT EVALUATIONS OF THE FUTREX-5000

There have been many independent evaluations of the accuracy and reliability of the instrument. The following summarizes some of the more pertinent papers.

Joint University of Maryland and Southern Connecticut State University Study - In 1989, Davis et al performed a comparison of the FUTREX-5000 results versus underwater weighing on a total of seventy-529 subjects (33 male and 39 female).[9] This study was done in conjunction with the Optifast Weight Loss Program, and thus, included a reasonable number of morbidly obese people.

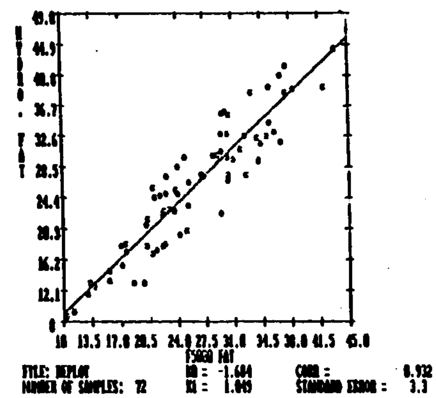
The body fat range of these people (from underwater weighing) was from 8 to 49%. Ages were from 18 to 72.

To avoid the possibility of bias from a single underwater weighing facility, the tests were performed at two separate institutions; the University of Maryland's facility in College Park, Maryland, and the Southern Connecticut State University's facility in New Haven, Connecticut.

The Figure 17 presents the results of this study; the overall correlation of FUTREX-5000 compared to underwater weighing was 0.92, with a standard error of 3.3.

FUTREX-5000 Evaluations
UM and SCU F-5000 Calibration Study

- Population
  - 72 subjects (33 M, 39 F)
  - Body fat Range 8 to 49%
  - Age 18 to 72
  - UWW at UM (42) and SCU (34) (4 dual tested)
- Results
  - F-5000 vs. UWW R=0.92, SEE=3.3



Davis, Dotson, Manny, Bililing 1989

Figure 17.

Study of Native Japanese - In 1990, S. Awai et al from Tokyo University performed a study of native Japanese.[10]

The results of their study, Figure 18, illustrates that near-IR interactance (i.e. FUTREX-5000) had a correlation on underwater weighing of 0.88 with an accuracy of 3.2%. This is approximately the same results as was achieved by Davis et al.

Youth Studies - In 1988 and 1989 Dotson et al performed an Evaluation OF NIR For Body Composition In Children And Youths".[11] In performing these studies, 1,171 students were measured (585 male, 541 female). The ages of the students were from 5 to 18 years old, and covered a significant racial mix (50% Caucasian, 30% Afro-American, 15% Oriental, and 5% unspecified).

From the 1,171 students, a subsample of 200 volunteers had body fat determined via underwater weighing at the University of Maryland facility (75 male, 125 female). All 1,171 were measured via skinfolds using the AAHPERD 1988 method, had optical measurements made using the FUTREX-5000 at the biceps site.

Figure 19 presents the scatter diagrams for both the preadolescent and the adolescent. The correlation for the preadolescent is 0.82 and the correlation for the adolescent is 0.88.

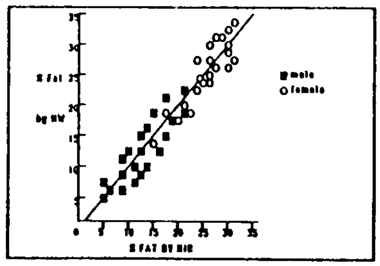
The authors felt that these were excellent results, particularly considering that they used chronological age as a parameter as opposed to a more sophisticated type of maturity index.

FUTREX-5000 Evaluations
Study of Native Japanese

- Population

	Males mean ± SD (range)	Females mean ± SD (range)
n	67	52
Age (yr)	28.5 ± 12.7 (18 to 58)	30.6 ± 11.8 (18 to 56)
Height (cm)	170.7 ± 6.1 (159 to 185)	157.9 ± 5.4 (144 to 171)
Weight (kg)	62.5 ± 7.3 (50 to 83)	51.9 ± 5.2 (41 to 65)
%Body Fat	14.1 ± 5.2 (5.1 to 28.1)	23.7 ± 4.6 (14.1 to 33.9)

- Results



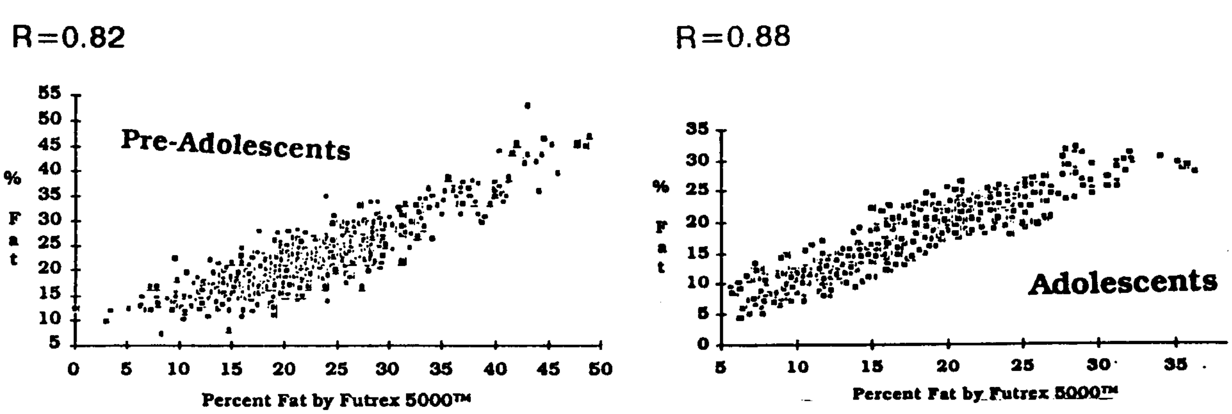
	NIR2	HW	SF
nir1	1.00(0.02)	-0.88(3.3)	-0.83(4.0)
nir2		-0.88(3.2)	-0.84(3.0)
HW			0.87(3.4)

note: all data p < 0.001

Sawai, Mutoh, and Miyashita (An. Tokyo Un. 1990)

Figure 18.

- Results



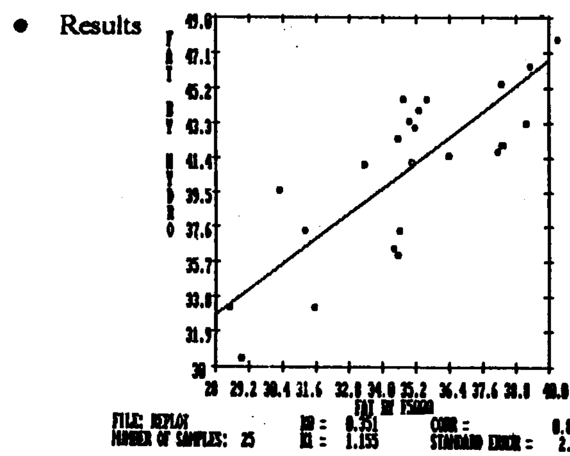
Dotson, C, and Davis, P, FACSM; AAHPERD '88,'89

Figure 19.

Study of Obese Women - Wadden of the University of Pennsylvania performed an evaluation of the FUTREX-5000 versus underwater weighing on 25 obese women. These women varied between ages 18 and 65, and had body fat between 32 to 50%.[12]

The results, Figure 20, provided a correlation of 0.82 with a standard error of 2.8%. The reason for the lower correlation value was the limited range of the percent body fat that this study covered. It is significant that the standard error is approximately the same standard repeatability error in underwater weighing at that facility.

FUTREX-5000 Evaluations
Study of Obese Women

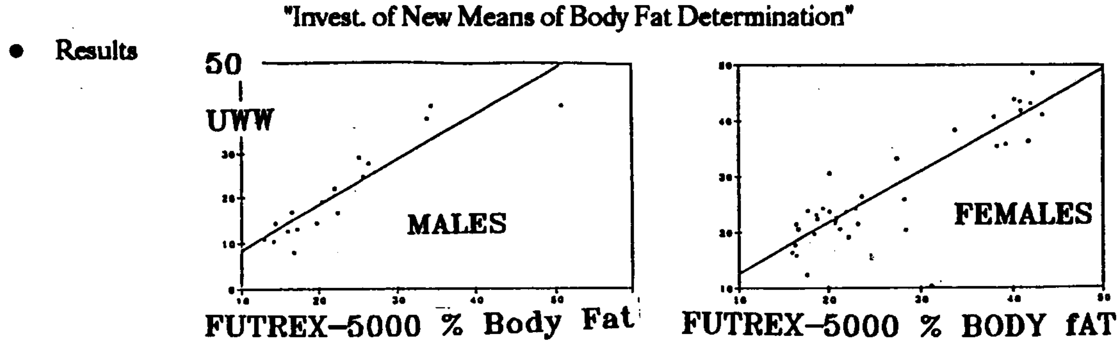


Wadden, T; Un. of Pennsylvania, 1989

Figure 20.

Temple University Study - O'Shea in 1988 studied a population of 55 subjects (20 male and 35 female). The age range was from 18 to 50. The body fat range for the women covered approximately 10 to 49%, and for men from 8% to 40%.[13]

FUTREX-5000 Evaluations
"Invest. of New Means of Body Fat Determination"



Reliability Test Data

Subject #	Age	Sex	1st Read.	2nd Read.
1	25	F	15.25	15.80
2	25	M	17.50	17.45
3	22	M	19.75	20.10
4	35	F	19.40	20.65
5	25	M	20.25	21.80
6	25	F	19.35	19.60
7	28	F	19.50	19.65
8	29	F	22.25	23.35
9	25	M	19.10	19.35
10	28	F	22.55	22.80
11	42	F	21.55	21.85

O'Shea,C. Temple Univ Press 1988

Figure 21.

The method used was to compare the FUTREX-5000 results with underwater weighing. The results obtained by O'Shea were essentially identical to the prior studies. However, perhaps a more interesting result was the study of reliability of the FUTREX-5000 measurement. To study reliability, O'Shea measured eleven subjects in an orderly manner. Each subject was read two times, three minutes apart. That data was then averaged and classified "first reading". The same subject was re-measured three days later in a similar fashion. The average data for that subject was then listed under the "second reading".

Figure 21 illustrated the excellent reliability (i.e. reproducibility) of the FUTREX-5000. It confirms that one of the major advantages of the interactance technique is the ability to have reliable, repeatable measurements.

__Other Comparative Studies__ - Figure 22 summarizes some of the other studies that have been completed on comparing the interactance technique to other methods of body fat determination. As shown, most of the studies have confirmed the original Davis et al results.

FUTREX-5000 Evaluations
OTHER COMPARATIVE STUDIES (In Process)

FUTREX-5000 ON NEONATES
(Children's Hospital Kansas City, Mo)
(Also in Japan and Ireland)

F-5000 vs SF Correlation = 0.82 (Mo)
F-5000 vs. SF Correlation = 0.96 (Japan)

FUTREX-5000 ON GIRLS NEAR PUBERTY
(Dr. David Nielson, Univ. of Iowa)

F-5000 vs. UWW Correlation = 0.89
F-5000 test-retest Correlation = 0.99

FUTREX-5000 ON FIREFIGHTERS
(Davis, P., Dotson, C.)

F-5000 vs UWW Correlation = 0.94
(36 subjects)

FUTREX-5000 FOR WOMEN
(Heyward, V.; Univ. of New Mexico)

F-5000 vs. UWW Correlation = 0.96
S.E.P. = 37%

-----MANY OTHERS-----

Figure 22.

11. Summary

The use of near-infrared measurements for providing quantitative measurement is a well-established technique. It has been used in the agricultural/food industry for over twenty years and over 100,000 units are in use.

In general, near-infrared has proved to be at least as accurate as the underlying analytical procedures that it is compared against. In the measurement of fat, near-infrared techniques have proven to have a measurement accuracy at least equal to the official ether extract procedure for ground and pureed meats. For example, on small meat samples, the ether extract procedure has an accuracy of 0.05%. On these types of samples, the near-infrared interactance technique has proven to provide the same level of accuracy.

In the measurement of body composition, the commonly accepted "gold standard" is underwater weighing. However, it is well known that underwater weighing has significant errors associated with it due to residual air volume, degree of hydration, and assumptions concerning bone density. Thus, in general, underwater weighing technique is usually considered to have an accuracy of 2% to 3%.

Since all other body composition analysis methods must be compared to underwater weighing, they can not be proven to be better than underwater weighing; underwater weighing being the reference technique. Thus, evaluation of near-IR approach (i.e. the FUTREX-5000) against underwater weighing cannot provide better accuracy than 2% to 3%.

Therefore, although intuitively it is believed that multiple site near-IR measurements should yield better accuracy than the single site biceps measurement, it cannot be proven because underwater weighing is the limiting characteristic. This has been substantiated through a number of independent studies that have demonstrated that the single site (i.e. the biceps) provided similar accuracy to underwater weighing.

In conclusion, it is believed that the desirable characteristic of near-IR body composition analysis - - - e.g. not require any fasting, disrobing, or the use of a skilled operator - - - is perhaps its most attractive feature. Simply stated, the near-IR method is able to be reliably used in a wide range of applications.

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